Improve Doherty Amplifier in efficiency and output power

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The Doherty Amplifier, invented almost 100 years ago, is used in an increasing number of radio transmitter applications to improve energy efficiency. There are numerous ways to build the Doherty PA.

This article begins with an overview of Linearization and Efficiency Enhancement and against that backdrop, highlights the associated challenges and some of the numerous solutions. Finally, an alternative design flow supported with a case study, which provides the engineer with a novel insight into their design, enabling them to achieve the best performance-cost compromise. The article can be read in conjunction with a recent Rohde & Schwarz white paper on optimizing a Doherty Amplifier.

Linearization & Placing the Doherty

The four key technical performance definers in a Transmit RFFE (TxRFFE) are efficiency, output power, linearity and bandwidth. The latter three of those parameters are often dictated by system requirements, for example, a communication standard. The former, (energy) efficiency, is the differentiator. All other things being equal, a higher efficiency figure for a frontend is preferred.

Devices used in RFFE have imperfect linearity characteristics. This prevents them from being fully utilized when used merely as drop-in components. The linearity of a TxRFFE can be improved by implementing a linearization scheme. Typically, this will increase the raw cost of a TxRFFE, but it also means that a combination of efficiency, linearity and output power will be improved.

There are numerous linearization methods in the literature, stretching back at least to the Feedforward and Feedback [Black, 1928][Black, 1937] patents. Arguably, the use of non-linear Predistortion dates similarly, to the invention of companding [Clark, 1928]

These schemes may be classified [Lloyd, 2016] according to their modus operandi (Fig 1). One way of dividing the linearization pie is to identify whether a scheme predicts or extracts its unwanted signal, and whether that unwanted correction is applied before or after its creation. Classification is useful in order to understand general properties and identify the best tool for the job.

Linearization Methods

		Impediment Generation	
		Predicted/Synthesized	Measured/Extracted
Correction Location	Pre-source	Digital Pre-distortion Analog Pre-distortion	Cartesian Feedback Polar Feedback
	Post-source	~~Analog Post-Distortion~~ Composition Schemes	Feedforward Fixed Filtering (e.g. Band Pass)

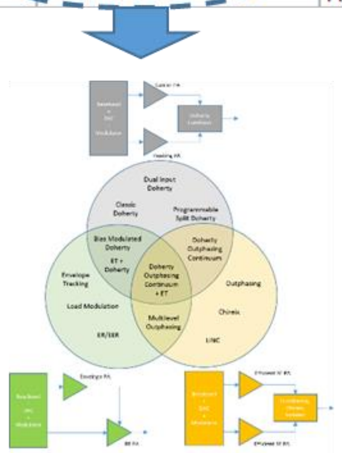

Fig 1 - The proposed classification of Linearization schemes, with examples, with the “predicted post-correction” family of MISO Transmitters (Multiple-Input, Single-Output) broken out.

Feedforward is an example of a measured, post-correction scheme, Feedback a measured pre-correction scheme. Finally, Predistortion is a predicted, pre-correction scheme. For example, predictive schemes rely on the unwanted signal being generated. This can be potentially onerous in widerband and lower power systems for digital predistortion (DPD). On the other hand, predictive schemes do not require that some distortion exists, therefore, can potentially completely eliminate distortion.

Missing so far from these observations, is a whole class of linearization techniques using predictive post-correction. This family of techniques has also been heavily researched and documented over the last 100 years. Outphasing [Chireix, 1935], Envelope [Kahn, 1952] and Doherty [Doherty, 1936] transmitters, along with their hybrids [Choi 2009], [Andersson, 2013], [Chung, 2009] are examples of such techniques, except they have been primarily marketed as efficiency enhancement, rather than linearization, techniques.

In their purest forms, Envelope and Outphasing schemes construct their signals from efficiently generated, but non-linear components, using multiplication and summing of their paths, respectively. Doherty comprises a reference path (often referred to as “main” or “carrier”) and an efficiency path (referred to as “peaking” or “auxiliary”).

A more comprehensive mathematical analysis of the Doherty is performed in a plurality of texts, and is beyond the scope of this article. For further information, the reader is referred especially to Cripps [Cripps, 2006].

Doherty Implementations – From the Zeroth Embodiment to the Magnum Opus

Arguably, the most common (and often quickest) starting point for Doherty amplifier realization (Fig 2) comprises:

- A fixed RF input (to the final stage) power splitter
- A Main and Auxiliary amplifier, differently biased (e.g. using “Class AB” and “Class C”)
- A “Doherty combiner”, made from a quarter-wavelength transmission line.

In most applications, this architecture does not provide sufficient power gain, at least not from a single, final stage. Therefore, additional gain stages are cascaded ahead of the input.

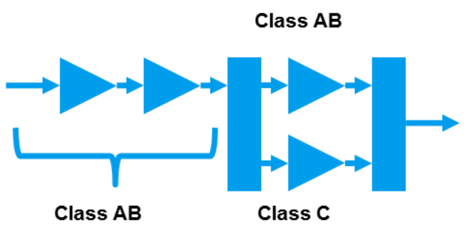

Fig 2 - Simplest, zeroth implementation of the Doherty amplifier. Here, the Doherty is realized using a single stage of Class AB and Class C biased devices, between a fixed RF input split and Doherty combiner. Two additional class AB stages are added before the Doherty input split, to increase gain.

Criticisms of this most commonly used implementation might include:

- No method for compensation gain-phase variations (in any domain), after design freeze.
- Both efficiency and output power are traded-off because of the bias class (in effect, an open loop analog circuit, the class C bias, is driving this)
- Efficiency enhancement of only a single stage, in a multistage cascade, limits the performance improvement, especially as gain diminishes at higher frequencies

Another perspective here is that the Doherty engine is created from an open-loop mechanism. Several key functional mechanisms are derived from the bias points of the transistors. Thus only one or two handles are provided, upon which multiple critical adjustments rely, once other variables are nailed down (e.g. phase offsets, splitter design, etc.)

Challenges (of the Zeroth Embodiment)

One of the methods by which Doherty improves efficiency is load modulation. The engine that drives that load modulation is the difference in output currents, sourced into the combiner from the two (or more) amplifiers. Since the engine can only approximate Doherty operation requirements, the challenge for the engineer is to enable that engine to approximate it with the best, but still appropriate, cost-performance paradigm:

Some of the potential hindrances or impediments to Doherty performance are as follows (Fig 3):

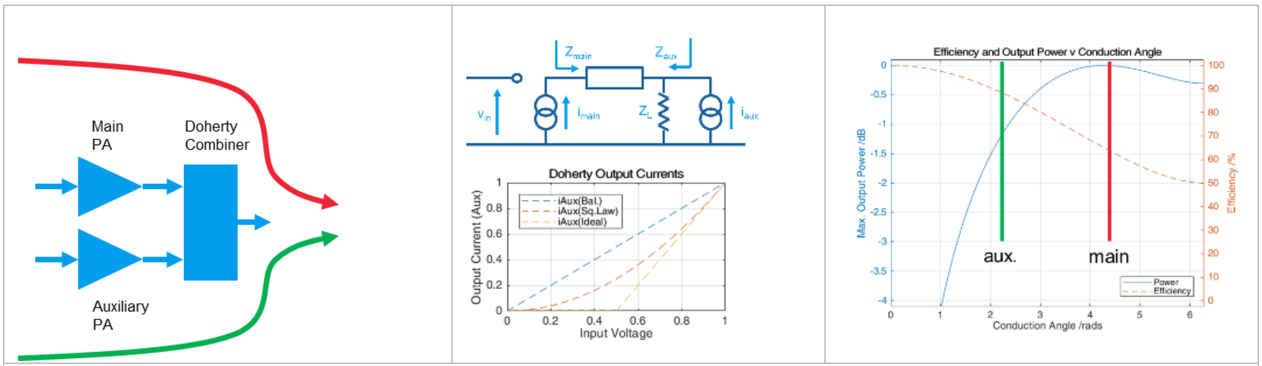

Fig 3 - Three exemplary challenges of Doherty Amplifier realization. (a) amplitude and phase matching in the combining, (b) the dog-leg or hockey-stick amplitude response, (c) differential biasing power-efficiency trade-off used to drive the Doherty engine [Cripps, 2006].

1. Amplitude and phase matching of the signals incident to the combining node, especially over frequency.

Deviation from the ideal can cause degraded efficiency and output power. Potentially, it can be more destructive, especially given that the devices are intentionally not isolated, relying on mutual interaction with each other through the combiner to create the efficiency enhancement effect.

2. The Doherty engine demands that the output current of the Auxiliary path ideally exhibits a dog-leg or hockey stick characteristic.

Failure to achieve sufficient compliance with that ideal, is often the primary reason for not realizing the famous efficiency saddle point. In fact, as the achieved characteristic tends from the “ideal” to the “linear”, the Doherty amplifier increasingly behaves like its quadrature-balanced relative, albeit with a non-isolated combiner, especially in its efficiency characteristics.

3. The commonly used “differential biasing” of Main and Auxiliary (e.g. in class AB and class C) forces both output power and efficiency of both amplifiers to be degraded.

As Cripps showed, the continuum of quasi-linear amplifier classes from A to C, which theoretically operate with sinusoidal voltages across their sources, vary in their maximum output power and efficiency characteristics.

At the same time, if biasing is used to create the difference engine, as is the case in the classical Doherty embodiment, then there is intrinsically always a trade-off of output power and efficiency happening. Simultaneously then, differential biasing increases the Doherty effect, but decreases the performance available.

Variants and Improvements on the Zeroth Embodiment

The following are variations on the basic concept, which might be more appropriate for some applications. Commonly used variants, plus their hybrids, include:

- Multiple gain stages (inside the Doherty split-combine)
- N-way Doherty
- Intentionally dispersive splitter
- Programmable splitter
- Bias Modulation
- Supply Modulation (adding a third efficiency enhancement technique, to the two already leveraged by Doherty)
- Envelope Shaping
- Digital Doherty

These variants, along with the classical implementation, offer different performance and flexibility options. Of the different handles available to the engineer, there are ostensibly three points in the product life cycle at which adjustment can be made.

- Design time.

- The engineer can modify the design parameters as they wish, but those parameters will be passed for production as fixed values (e.g. fixed input splitter design)

- Production time
  - Parameters may be modified or tuned during the production process, typically based on measurement data, and then frozen or fixed-programmed. An example includes the nominal bias voltage used to generate a target bias current in the devices.
- Field operation
  - Parameters may be updated, either continuously or at specific points in time, once the equipment is deployed. These may be open- or closed-loop. Examples include temperature compensation circuitry. Open loop concepts rely on sufficiently predictable behaviors, closed loop concepts might require built-in measurement and control.

This all adds up to a plurality of solutions and no single, best solution. It is just as important for the engineer to be aware of their own manufacturing and supply capabilities as the high-frequency design challenges and trade-offs.

At the opposite end of the solution spectrum from the Zeroth embodiment then, is the Digital Doherty (Fig 4).

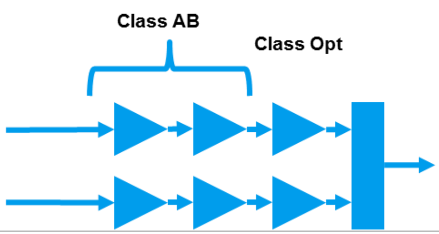

Fig 4 - The Magnum Opus realization of the Doherty Amplifier – “Digital Doherty”. The “Class Opt” referred to for the final stage indicates that the choice of bias point is emancipated.

This architecture is characterized by an input split, which stretches back into the digital domain, prior to digital-to-analog conversion (DAC).

The ability to apply digital signal processing (DSP) techniques to the signal applied to both paths gives potentially unsurpassable performance from a given piece of RF hardware.

Compared to the Zeroth implementation, it can offer 60% greater output power, 20% more efficiency, 50% more bandwidth without degrading predictive, pre-correction linearizability. [Darraji, 2016]

Alternative Design Flow - Measurement Aided Development

How does the engineer best identify the implementation for their specific task?

Where possible, it is highly advisable to build simulation environments to correlate with the design, at least to understand trends and sensitivities. The initial simulation enables a significant part of the development to be covered quickly. Inputs to this first step might include load-pull data or models for the candidate devices, a theoretical study of the combiner and matching network responses, evaluation boards and measurement data, empirical data, or something completely different.

With this stable starting point in place, it is also now possible to complement the development process with a measurement-aided development step.

The starting point for this measurement exercise is a dual-input Doherty DUT – comprising two input ports, input and output matching networks, active devices, bias networks, and the Doherty combiner.

By measuring the prototype Doherty as a dual-input device, it is possible to obtain a greater insight of the performance limitations, trade-offs and reproducibility behaviors that might be expected in a production environment.

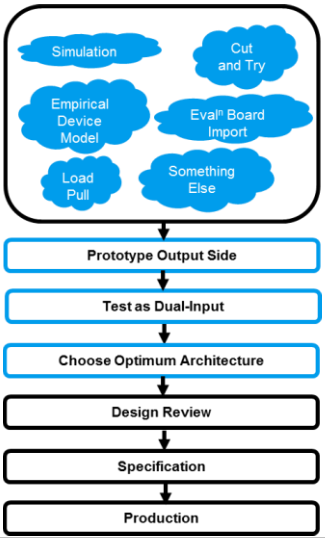

Fig 5 - Measurement-aided Design introduced to the typical Doherty design flow.

Dual-Input Measurement Set-Up

Critical to the test set-up (Fig 6) are two signal paths, whose signals may be varied relative to each other. The test set-up naturally needs to be sufficiently stable for the period of the measurement. In addition to being able to apply precision, repeatable amplitude and phase offsets to the same signal, it is advantageous to be able to apply non-linear shaping to at least one of the signal paths.

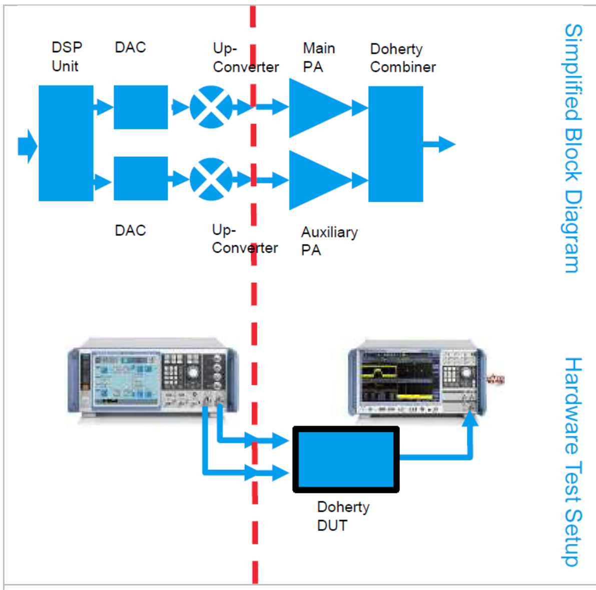

Fig 6 - The generalized test set-up, for Doherty Amplifier development, with DUT shown in yellow.

The measurement algorithm may be rapid or more exhaustive. It may be programmed to seek out optimum values directly for desired parameters. It might equally be configured just to characterize over a wide sweep range of parameters.

In a simple case, the engineer might want confirmation merely of the best-case quantities, and their relative amplitude/phase balance values. In another case, the engineer might like a more detailed sweep, for example, to enable a sensitivity analysis or a more rigorous solution space search.

The post-processing of these results can be as simple or sophisticated as the user wishes.

The case study measurements were performed on a state-of-the-art GaN Doherty Amplifier, intended for 5G NR operation in the 3.5GHz band, based on the Qorvo® TQP0103 device.

The amplifier was stimulated using differentially linear and non-linear signals, the former sweeping input power, amplitude and phase differences, the second added a variable shaping (amplitude-dependent) function, at two frequencies. Performance quantities including current consumption, ACLR, output power and output peak-to-average power ratio were measured.

Case Study – Linear Analysis

Measurement results were collated for post-processing in MATLAB ®.

In the most basic analysis of the linear case, energy efficiency at a specified power level and saturated power were plotted for the different amplitude- and phase-differences. These are shown in Fig 7.

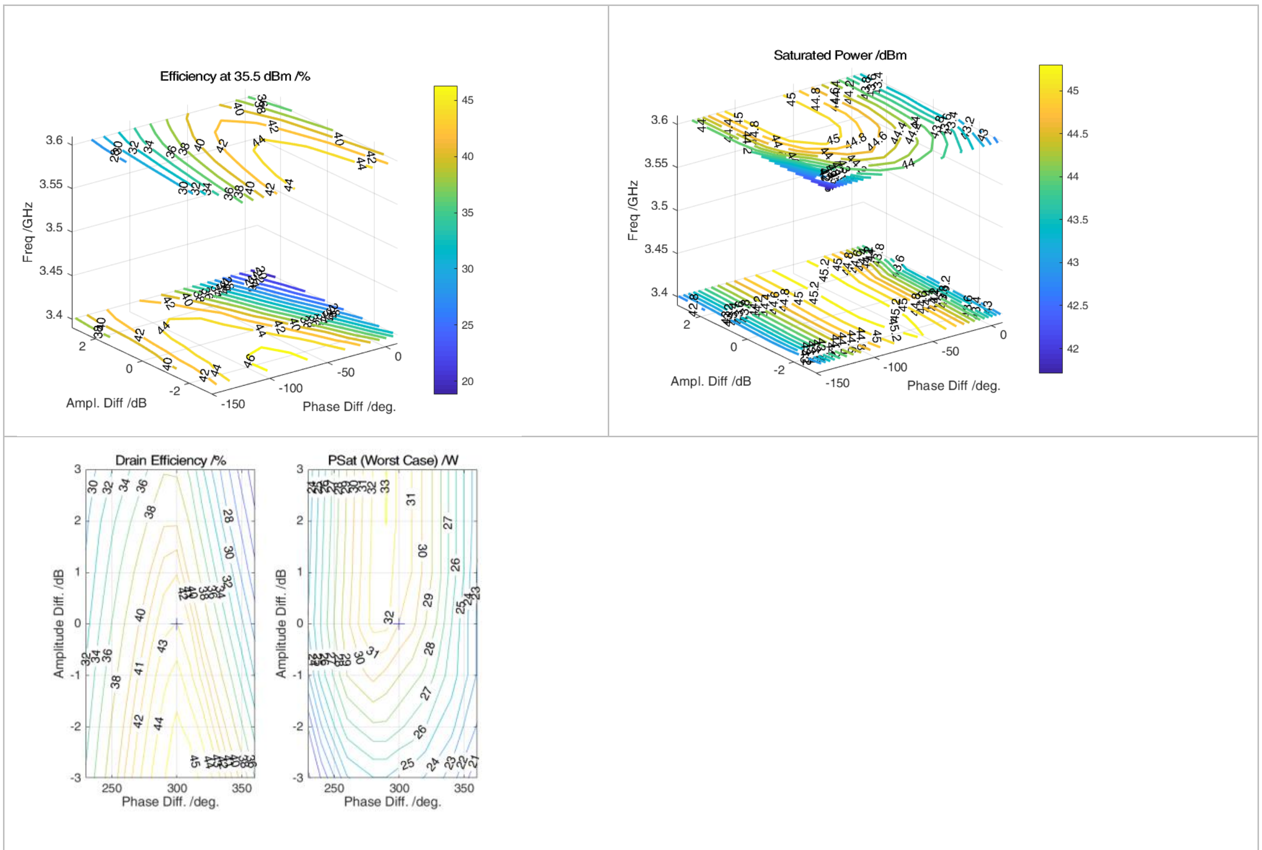

Fig 7 - Measurement of the dual-input Doherty amplifier in “Linear” mode. Two frequencies, using a noise-like signal, illustrating (a) efficiency at a fixed power level, (b) saturated power and (c) the worst case of each, for each amplitude-phase difference.

In the basic Doherty embodiment, a quasi-constant amplitude-phase split value is chosen for the operating frequency. The efficiency and saturated power for these amplitude-phase values can be ascertained by extracting the worst-case performance at the two test frequencies.

With a nominal amplitude-phase split selected, a perturbation representing natural variations in production may be added. Using a look-up table concept, the bulk effect of these part-to-part variations can be seen (Fig 8). Firstly at the two frequencies independently, then the simultaneous aggregate effect. Paradoxically (in this case), the vast majority of the part-to-part variation is in the target variable, efficiency.

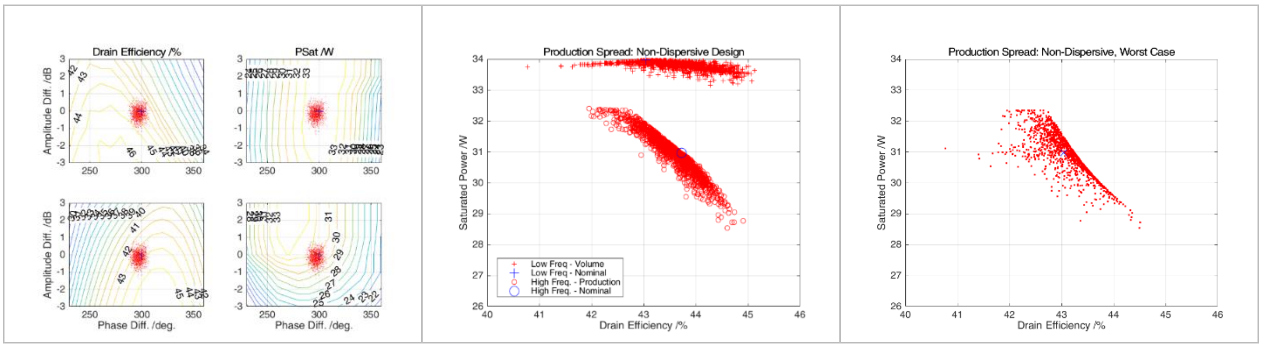

Fig 8 - Industrial analysis of the Doherty Amplifier using a **fixed RF input split** showing (a) dispersion of gain-phase variation across the population, (b) saturated power vs efficiency using a look-up concept and (c) the cumulative, worst-case effect.

By taking an alternative approach to the input splitter design, some of this variation can be engineered out.

In the next analysis scenario (Fig 9) using the same measurement dataset, a dispersive input splitter design is assumed. That means different amplitude and phase differences, at the two design frequencies, are used. The dispersive design advantageously allows the stacked contours plots shown in Fig__ to, in effect, be slid over one another.

Applying that same population of part-to-part variation to this new scenario gives a quite different result, as shown in Fig__, demonstrating both a higher mean-, and lower standard deviation values, to efficiency.

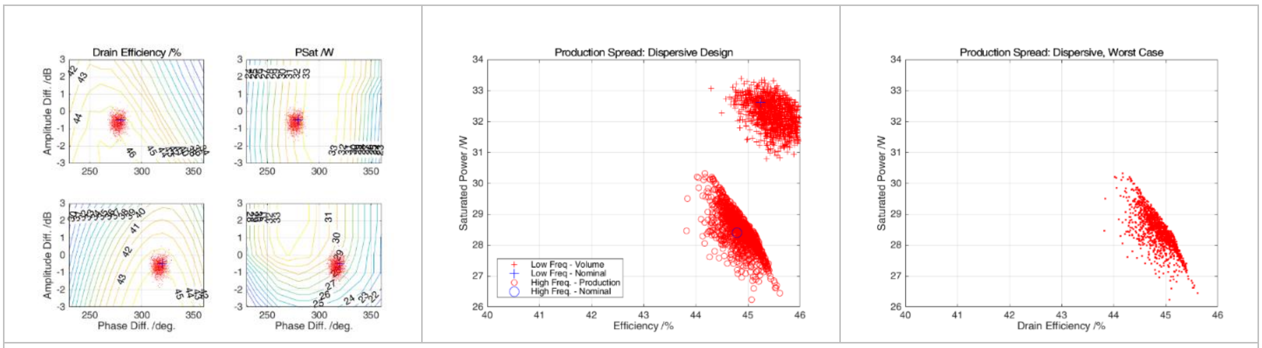

Fig 9 - Industrial analysis of the Doherty Amplifier using an **intentionally dispersive RF input split**

Case Study – Non-Linear Analysis

By directly generating signals for the two paths in the digital domain, Doherty Amplifier deficiencies are significantly reduced. Additionally, the simple part-to-part gain-phase variations (shown in the linear example) may be eliminated.

Illustratively, not exhaustively, the Auxiliary/Efficiency path was programmed with a square-law shaping function applied both to amplitude and phase. The phase “start” and “end” values (i.e. phase with zero and maximum input amplitude) was varied randomly.

With the bias point of the two amplifiers commoned, only a trade-off of output power and efficiency remains, rather than both those plus the Doherty difference engine magnitude.

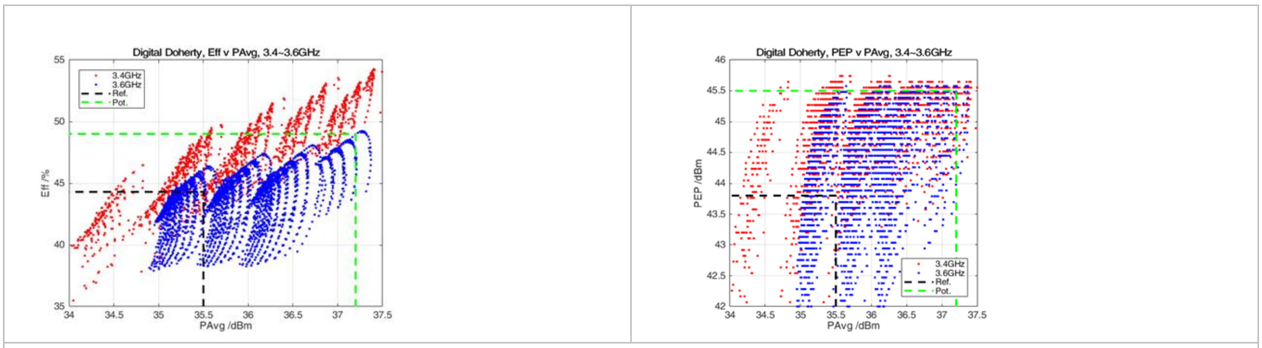

Fig 10 - Measurements of the dual-input Doherty using a **non-linear shaping** (in this case, square-law shaping), with randomized phase values, showing (a) efficiency versus average power and (b) peak envelope power (PEP) versus average power.

In a baseline test, by driving common biased amplifiers with a linearly differential signal, the equivalent “balanced” performance can be ascertained. The saturated output power available in this mode was 0,5dB (12%) higher than the differential biased case. In this case, that figure represents the “cost” of operating the Doherty engine using differential bias points.

The scatter plot of random shaping functions applied to the Auxiliary/Efficiency path illustrates a typical, but not exhaustive, locus of performance (Fig 10).

The saturated output power is now 1,7dB (48%) higher than the conventional Doherty case, suggesting that a 1,2dB (32%) improvement is derived from better amplitude-phase matching of the signal paths.

The 1,7dB/48% improvement in saturated output power means that the amplifier may be operated at that increased average output power without compromising headroom. That increase in average power is associated with a 5 percent points increase in efficiency (from 44% to 49%).

Alternatively, devices with 48% smaller periphery may be used to achieve the same, original, target output power. Taking into account the expected part-to-part variation, this periphery shrinkage could be significant reduced yet further.

Conclusions

Significant improvements in Doherty performance can be achieved by addressing the input side. A measurement-aided methodology for extracting and understanding what is possible is presented. The illustrated parameters, efficiency and saturated power are merely exemplary, but in the majority of cases represent the two most important parameters.

The use iofa Doherty Amplifier design, at least either of an (i) intentionally dispersive or (ii) programmable input split, can improve performance, especially in the industrial domain.

With the use of non-linear input splitting or shaping (so-called Digital Doherty), according to peer reviewed research, the performance advantage could be 60% more output power, 20% more efficiency, 50% more bandwidth with any degradation in predictive linearization. In this simple case, the improvements over a fixed bandwidth were 47% for output power and 11% for energy efficiency.

Regardless of which architecture is ultimately used, by providing a more detailed and rigorous insight, this methodology can improve both the time-to-market and improve the cost-specification paradigm.

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